# Studies of Ionospheric Irregularities: Origins and Effects

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Award Number: N00014-09-1-0295
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## LONG-TERM GOALS

We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.

## OBJECTIVES

The scientific objectives of the project are:

(1) To investigate space weather and its effects on GPS, including the characterization of L-band scintillations and scintillation effects on GPS signals and receivers;

(2) To investigate the origin of ionospheric irregularities, which lead to ionospheric scintillation storms, through deployment of GPS scintillation receivers at equatorial latitudes, regionally in South America, at mid-latitudes (Hawaii, Ithaca, Puerto Rico, Utah), and at high latitudes (Norway);

(3) To develop GNSS receivers (WAAS, Galileo, and modernized GPS) that can assess the effect of scintillations and space weather on modernized GNSS signals;

(4) To develop space-based GPS receivers for sounding rocket and satellite applications that can remotely sense the ionosphere, thermosphere, and mesosphere.

## APPROACH

Our research focuses on the study of space weather and the impact of space weather on GPS and GNSS receivers. Our approach is primarily experimental, and we have a reputation for producing cutting-edge instrumentation and developing successful experiments. The vast majority of the universe exists in a plasma state and we focus on our own upper atmosphere and ionosphere as natural laboratories for studying space weather and as an environment that affects satellites and their signals.

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **30 SEP 2009** | **Annual** | **00-00-2009 to 00-00-2009** |

4. TITLE AND SUBTITLE
**Studies Of Ionospheric Irregularities: Origins And Effects**

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
**Cornell University,School of Electrical and Computer Engineering,302 Rhodes Hall,Ithaca,NY,14853**

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES
**Code 1 only**

14. ABSTRACT
**We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **Same as Report (SAR)** | **4** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

This yields a mix of applied and curiosity-driven research. By primarily employing sounding rockets and ground-based instrumentation, graduate students are able to participate in the full range of research and develop into future leaders. For example, Cornell University's development of a GPS receiver for measuring fast amplitude scintillations has led to a global program with receivers deployed at multiple sites across South America, Africa, and China. Several Ph.D. students and postdocs from Cornell and Brazil have been trained using these receivers. This receiver not only monitors ionospheric scintillation but additionally measures ionospheric drifts. This effort also leverages our development of GPS software receivers and space-based GPS receivers.

## WORK COMPLETED

(1) We developed a prototype real-time dual-frequency (L1CA/L2C) software GPS receiver based on a DSP chip.

(2) We developed a compact and low-power RF front-end for L1CA and L2C.

(3) We conducted the first L1CA/L2C measurements of ionospheric scintillation using multiple receivers.

(4) We developed a brass board L5 tracking circuit based on an FPGA.

(5) We developed an ionospheric scintillation model for use in commercial GPS signal simulators.

(6) We authored a cover story in *Inside GNSS* on GPS and scintillation.

(7) We developed a GPS spoofer.

(8) We authored a cover story in *GPS World* on GPS spoofing.

## RESULTS

(1) We demonstrated how amplitude and phase scintillation are related. Deep amplitude fades are accompanied by fast half-cycle phase shifts. This has important implications for how to design scintillation-resistant receivers.

(2) We developed a dual-frequency GPS receiver operating on a digital signal processing chip. This software is portable and will lead to an entire new family of practical software GPS receivers.

(3) We demonstrated a GPS spoofer based on a GPS software receiver. This led to a cover story in *GPS World*.

## IMPACT/APPLICATIONS

Our work with GPS receivers and space weather continues to be important in understanding and predicting the behavior of GPS receivers in the presence of both solar radio bursts and scintillation. In the future, our receivers will be critical to evaluating the impact of space weather on GNSS signals. Our past work in determining the shape of fade patterns is important to understanding how velocity resonance will occur and potentially produce loss of lock or even loss of navigation in GPS receivers. Our recent work with the WAAS signals will lead to understanding the significance of scintillations on this system. Our continued development of software receivers looks to the future when modernized GPS signals will be available and dual-frequency measurements of TEC should be inexpensive.

We have demonstrated that scintillation during deep fades has canonical behavior. That is deep fades are accompanied by half-cycle phase jumps. This will lead to new designs for GPS receivers that can track robustly in the presence of scintillation.

We have demonstrated the design and operation of a GPS signal spoofer. The significance of this demonstration is how easy it was to design the spoofer. The impact is that, within 5 years, GPS spoofing is likely to be common, and the fabrication of GPS spoofers by students who have not yet achieved a college degree in engineering will be possible.

**TRANSITIONS**

The DSP software technology has been leveraged to win an STTR from the USAF. The STTR is association with ASTRA to develop inexpensive GPS space weather receivers that can be connected in large arrays.

**RELATED PROJECTS**

See above.

**PUBLICATIONS**


Effect of intense December 2006 solar radio bursts on GPS receivers, A.P. Cerruti, P.M. Kintner, Jr., D.E. Gary, A.J. Mannucci, R.F. Meyer, P. Doherty, and A.J. Coster, *Space Weather, 6*, S10D07, doi:10.1029/2007SW000375, 2008. [published, refereed]

GPS L-band scintillations and ionospheric irregularity zonal drifts inferred at equatorial and low-latitude regions, M.T.A.H. Muella, E.R. de Paula, I.J. Kantor, I.S. Batista, J.H.A. Sobral, M.A. Abdu, P.M. Kintner, K.M. Groves, and P.F. Smorigo, *J. Atmos. Solar-Terr. Phys.*, *70*(10), 1261-1272, 2008. [published, refereed]

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Evaluating GPS Receiver Robustness to Ionospheric Scintillation, J.C. Hinks, T.E. Humphreys, B.W. O'Hanlon, M.L. Psiaki, and P.M. Kintner, Jr., *Proc. 2008 ION GNSS Conf.*, Sept. 16-19, 2008, Institute of Navigation, Savannah, GA. (Received best presentation award in session of 8 papers.) [published, refereed]

Assessing the spoofing threat: Development of a portable GPS civilian spoofer, T.E. Humphreys, B.M. Ledvina, M.L. Psiaki, B.W. O'Hanlon, and P.M. Kintner, Jr., *Proc. 2008 ION GNSS Conf.*, Institute of Navigation, Savanna, GA, 2008. [published, refereed]

Simulating ionosphere-induced scintillation for testing GPS receiver phase tracking loops, T.E. Humphreys, M.L. Psiaki, J.C. Hinks, B. O'Hanlon and P.M. Kintner, Jr., *IEEE Journal of Selected Topics in Signal Processing*, submitted, 2008. [published, refereed]

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Ionospheric zonal velocities at conjugate points over Brazil during the COPEX campaign: Experimental observations and theoretical validations, J.H.A. Sobral, M.A. Abdu, T.R. Pedersen, V.M. Castilho, D.C.S. Arruda, M.T.A.H. Muella, I. S. Batista, M. Mascarenhas, E.R. de Paula, P.M. Kintner, E.A. Kherani, A.F. Medeiros, R.A. Buriti, H. Takahashi, N.J. Schuch, C.M. Denardini, C.J. Zamlutti, A.A. Pimenta, J.R. de Souza, and F.C. P. Bertoni, *J. Geophys. Res*., 114, A04309, doi:10.1029/2008JA013896, 2009. [published, refereed]

Evidence of tropospheric effects on the ionosphere, T. J. Immel, B. Mende, M. E. Hagan, P. M. Kintner, and S. L. England, *EOS Trans., 90*(9), 69-70, 2009. [published, refereed]

Global positioning system and solar radio burst forensics, P.M. Kintner, Jr., B. O'Hanlon, D.E. Gary, and P.M.S. Kintner, *Radio Sci., 44*, RS0A08, doi:10.1029/2008RS004039, 2009. [published, refereed]

A data-driven simulation testbed for evaluating GPS carrier tracking loops in severe ionospheric scintillation, T.E. Humphreys, M.L. Psiaki, B.M. Ledvina, A.P. Cerruti, and P.M. Kintner, Jr., *IEEE Transactions on Aerospace and Electronic Systems*, 2009. [accepted, refereed]

Modeling the effects of ionospheric scintillation on GPS carrier phase tracking, T.E. Humphreys, M.L. Psiaki, and P.M. Kintner, Jr., *IEEE Transactions on Aerospace and Electronic Systems*, 2009. [accepted, refereed]

**PATENTS**

Civilian GPS Spoofing Testbed and Anti-Spoofing Countermeasures, 2009: **Patent application number 61/098,335.**

**HONORS/AWARDS/PRIZES**

2009 – 2010, Jefferson Science Fellow at the U.S. Department of State

2009, The Kristian Birkeland Lecture for 2009, Norwegian Academy of Science and Letters, Oslo, Norway

2008, Best Paper, International Ionospheric Effects Symposium (out of about 100)

2008, Best Session Paper, Institute of Navigation GPS National Meeting